Engineered Biochar as Construction Material

Diksha Pandey, Monika Chhimwal, and R. K. Srivastava

Abstract Biochar has a broad array of applications and is deployed in a variety of fields, including agriculture, sustainable development, and geoengineering. Various engineering methods have recently been developed and used to widen the application of biochar. One of them is the use of engineered biochar as a construction material. It can be exploited as a material for construction due to properties such as chemical stability, flammability, and low thermal conductivity. This chapter provides an overview of the properties of engineered biochar that make it suitable for the role of construction material. Factors such as pyrolysis conditions specifically, pyrolysis temperature, heating rate as well as pressure, along with various construction material properties have been depicted here. This chapter also highlights the implications of engineered biochar on the physical, mechanical, and durability aspects of building materials. Comprehensively, this engineered biochar is being used as a construction material due to a number of unique and interesting qualities, including the capability to build in a carbon-negative manner in addition to its applicability as an insulating material, biochar-based clay and lime plasters, building bricks, concrete and roof tiles. The chapter also aims to examine engineered biochar's current and future implications in the construction field.

Keywords Engineered biochar · Geoengineering · Adsorption · Pyrolysis · Construction material

1 Introduction

Biochar is a porous substance having various functional groups on the surface and is made from a variety of organic materials. Usually, pristine biochar has lower adsorption capacity than activated biochar, because of its low density and small particle size (Wang et al. 2017). To maximize the adsorption competency of biochar and its application in different areas, different engineering techniques have been proposed

D. Pandey (✉) · M. Chhimwal · R. K. Srivastava
Department of Environmental Science, CBSH, G.B.Pant University of Agriculture and Technology, Pantnagar U.S Nagar, Uttarakhand 263145, India
e-mail: diskshp99@gmail.com

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and used in soil improvement, waste management, geoenvironmental applications in addition to climate mitigation. The creation of an activated or modified form of biochar is called engineered biochar. Engineered biochar is a derivation of pure biochar that has been improved by physical, chemical, and biological means (e.g., properties such as surface area, porosity, cation exchange capacity, surface functional group, pH, etc.) and its adsorption capacity compared to pristine biochar (Yao et al. 2013).

In recent years, engineered biochar has gotten considerable attention as a building material, with a new trend of using it as an additive or replacement in cementitious composites (Restuccia et al. 2020; Belletti et al. 2019). Engineered biochar-containing constructional material provides much higher structural strength and improved permeability in contrast to pristine biochar. These findings suggest that engineered biochar has the capacity to be used as a carbon-sequestering admixture in construction materials and waste recycling methods (Gupta et al. 2017). Besides, the construction industry is expected to emit more greenhouse gases as the population grows and demands for a better-built environment increases, CO_2 emissions rapidly approaching a pivotal point that could result in irreversible climate change. The earth's capacity to neutralize the CO_2 emissions through the natural carbon cycle has been over-stretched. So reducing cement-based material productions could result to bring positive changes in the climate. Engineered biochar holds a lot of potential as a CO_2 absorbent material in construction applications (Akinyemi and Adesina 2020).

2 Properties of Engineered Biochar Suitable for Geoengineering and Advantages

The use of biochar as a material in construction applications is a relatively new area of research. Various raw materials and production processes have been used in various studies with the purpose of improving some properties of the end product via biochar. Pyrolysis temperature, pyrolysis rate, and pressure are regarded to be the most critical factors that determine textural properties among the several approaches that can affect the structure of the modified biochar (Newalkar et al. 2014). Pyrolysis temperature is significant because it is correlated to physical processes during biochar preparation such as volatile emission, char skeleton carbonization, pore creation, and broadening. The pyrolysis rate affects the physical mass transfer of volatiles at a specific temperature (Antal et al. 2003; Boateng 2007). Biochar also undergoes a secondary reaction at high temperatures, which enhances the formation of gas and liquid while decreasing the quantity of char. The physicochemical features of biochar, such as elemental composition, surface functional groups, and surface adsorption are affected by pyrolysis temperature (Shaaban et al. 2013; Yuan et al. 2014). Higher temperatures produced more activation energy, which resulted in more pore formation and enhanced surface area of biochar (Gupta et al. 2017; Ramola et al. 2020). Longer vapor residence time and lower temperature can result in increased biochar yield

(Encinar et al. 1996). Although residence time has little effect on char yield, it does change the composition of bio-oil and gaseous products (Mohamed et al. 2013). The textural properties of biochar are also influenced by pyrolysis pressure. Pyrolysis pressure has an impact on surface area as well as on biochar reactivity. When pressure was raised from 5 to 10 bar, surface area decreased, but it increased when pressure was raised from 10 to 20 bar (Newalkar et al. 2014). Apart from this, high chemical stability, low thermal conductivity, and low flammability are three qualities that make biochar ideal for use as a construction material.

2.1 Chemical Stability of Engineered Biochar

The chemical stability of biochar is mostly determined by the stability of fixed carbon in addition to the existence and abundance of oxygen groups and the presence of reactive oxygen. Moreover, the oxygen to carbon ratio (O: C ratio) is generally reported to estimate a threshold for relative stability of biochar. However, this ratio is not a robust indicator of inertness of carbon in biochar (Ndirangu et al. 2019). Chemical stability can possibly be achieved by incorporating biochar into cementitious materials for various construction applications. Better chemical stability of biochar is proficient when fast pyrolysis at a temperature of 800 °C is used. This is attributable to the fact that at a low pyrolysis temperature of 350 °C, only small amounts of carbon nutrients with low sorptive capacities are formed, that are required for sequestration (Novak et al. 2009; Gundale and Deluca 2006). At higher temperatures, higher carbon contents and aromaticity are produced accompanied by increased surface area needed for sorption while oxygen and hydrogen volume are reduced (Chen et al. 2008; Khanmohammadi et al. 2015). When biochar is blended with cementitious materials, the reactive areas are reduced, resulting in improved chemical stability. Apart from that, the use of engineered biochar diminishes alkali and alkaline base contents in soil amendment through biomass particle pulverization and thermal pretreatment. This aids in the fluidization of the combustion process while also reducing the biomass polymer structure (Kambo and Dutta 2015).

2.2 Low Thermal Conductivity

Low thermal conductivity is contributed by the involvement of a broad range of numerous nanopores, mesopores, and micropores on the surface of biochar particles; each with various sizes, shapes, and orientations which affect their performances differently (Askari et al. 2015) However, the distribution of pores depends on the raw material used and pyrolysis temperature (Brewer et al. 2014). Pores present in biochar prevent heat bridging inside the concrete, resulting in better building insulation. This is critical for lowering energy usage in building heating and cooling.

Depending on the temperature of biochar production, pores in biochar have different tendencies. When pyrolysis is carried out at a higher temperature, the volume of the pores normally expands (Bird and Ascough 2012). The average thermal conductivity of conventional concrete is between 0.62 W/(mK) and 3.3 W/(mK) (Cuthbertson et al. 2019). On the addition of a higher mixing ratio of biochar into a cement-based material, a thermal conductivity of 0.138–0.155 W/(mK) was achieved. This was 49.68–67.21% lesser than the conventional cement biocomposite (Lee et al. 2019) It was achievable because the pores in the additional biochar disrupt the thermal bridge in the cementitious materials to enhance the thermal insulation in the various applications. As a result, it is anticipated that energy expenses for heating and cooling structures will be reduced.

2.3 Flammability

Using biochar as a construction material, flammability is a critical determinant for fire safety. Biochar produced by slow pyrolysis shows no combustion front propagation (Zhao et al. 2014). However, fast pyrolysis produced biochar with a higher combustion front is by virtue of the presence of more reactive volatiles on the surface, such as alcohol and carboxylic acid groups, than slow pyrolysis produced biochar. Slow pyrolysis of biochar has a smaller surface area than fast pyrolysis and is more successful in reducing carbon-free radicals, which causes biochar to be less flammable. It was observed that besides the chemical stability, biochar are thermally stable materials and hinder fire propagation by slowing the passage of oxygen and fuel required for combustion in the presence of a carbonaceous wall. Thermal treatment of biomass produces free radicals that can react with oxygen, metals, and halogens in the environment (Amonette and Joseph 2009).

After production, the storage of biochar is reported to enhance the elimination of free radicals by reactivity with air and the rearranging of carbon planes, which reduces flammability. The majority of cement-based constructions are engineered with fire safety in mind. This is because engineered biochar, made by altering pristine biochar is prone to ignite when incorporated in buildings. As a result, extra caution must be taken to ensure that the substance is nonflammable (Table 1).

3 Effect of Engineered Biochar on the Characteristics of Building Materials

Engineered biochar has a tremendous influence on the physical, mechanical, and long-term durability of construction materials, in particular, cement and mortar (Fig. 1).

Table 1 Effect of pyrolysis conditions on properties of engineered biochar as construction material (Akinyemi and Adesina 2020)

S no	Raw material	Pyrolysis conditions	Changed properties of biochar	References
1	Peanut and Hazel nutshells	Pyrolysis at 850 °C for 1 h	- Increased toughness and flexural strength - 353% higher shielding efficiency - Reduced shrinkage	Khushnood et al. (2016)
2	Rubberwood sawdust	Pyrolysis at 450–850 °C	- Surface area of 220 m^2/g was recorded between 550 and 850 °C - Maximum C content in biochar at 750 °C - Maximum CO_2 adsorption capacity was recorded at 650 °C	Ghani et al. (2013)
3	Papermill sludge, rice husk, and poultry litter	Slow pyrolysis at 450 °C and gasification at 500 °C for 20 min	- 0.1% of pulp sludge and rice husk biochar enhanced mechanical strength - Poultry litter improved water absorption	Akhtar and Sarmah (2018)
4	Pine wood (Pinus taeda)	Pyrolysis at 600–1,000 °C	- With increase in pressure, char particles tend to become more spherical - Swelling increased with a decrease in externally applied pressure - Highest micropore area was recorded at 1,000 °C	Newalkar et al. (2014)
5	Wheat straw	Pyrolysis at 650 °C	- 0.5–1.5% biochar lead to 4.1–17.3% higher compressive strength	Ahmad et al. (2020)

(continued)

Table 1 (continued)

S no	Raw material	Pyrolysis conditions	Changed properties of biochar	References
6	Bagasse, bamboo	Pyrolysis, hydrothermal carbonization at 200 °C	- Surface area of biochar made at 600 °C increased 30 times - Thermal stability of char made by dry pyrolysis was higher than those made by hydrothermal carbonization	Sun et al. (2014)
7	Wood chips	Pyrolysis between 200 and 500 °C then gasified at 900 °C	- Increased dosages resulted in a slight reduction in compressive strength	Sirico et al. (2020)
8	Cotton stalk	Polygeneration by pyrolysis at 250–950 °C	- Increased pyrolysis temperature increased the degree of carbonization of chars	Chen et al. (2012a, b)
9	Softwood	Pyrolysis at 680° for 12 min	- Production parameters and features influenced the formation of strong covalent carbon leading to improved flexural strength and fracture energy	Cosentino et al. (2019)
10	Safflower seed press cake	Pyrolysis at 400–600 °C	- With increase in temperature from 400 to 500 °C, micropore volume and total pore volume increased - Above 500 °C, micropore volume decreased, which may be due to pore expansion due to heating	Angın (2013)

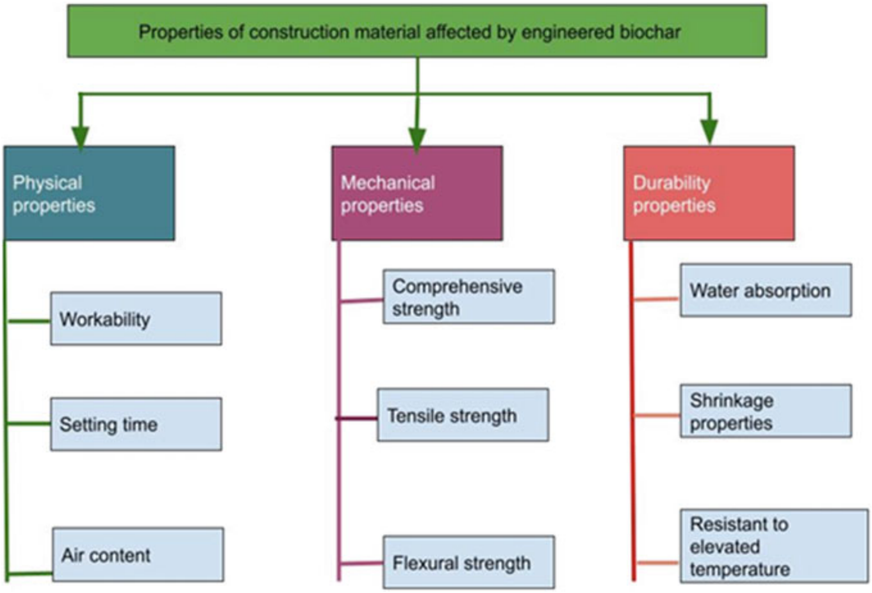

Fig. 1 Properties of construction material affected by engineered biochar

3.1 Physical Properties

Workability, setting times, and air content are some physical properties that can be affected by biochar. Since biochar has a lower specific gravity than Portland cement, it is expected to produce lower fresh and hardened densities in cementitious composites. The decreased specific gravity of the biochar, which results in a commensurate reduction in density, can be linked to the reduction in the dry and fresh densities of cementitious composites (Gupta et al. 2018a, b, c, d).

3.1.1 Workability

The workability of mortar mixtures containing food and wood waste engineered biochar was observed to be reduced. The addition of 3% biochar from wood and food waste reduced the flow of mortar mixtures by 13% and 10%, respectively. The increased water absorption of biochar as a substitute to Portland cement resulted in less water available for workability, resulting in reduced workability of mortar mixtures (Gupta et al. 2018a, b, c, d).

3.1.2 Setting Times

The use of biochar in mortar mixtures has been shown to lessen both the initial and final setting times of Portland cement (Gupta et al. 2018a, b, c, d). The reduction in set times was attributed to the reduction in free water and a filler effect of the biochar particles, resulting in higher cohesion of the mixture. The rapid hydration reaction caused by the incorporation of biochar into the mortar mixtures can also be responsible for the shorter setting time. Biochar particles operate as nucleation sites for cement hydration, resulting in the formation of extra hydration products when they are included in cement-based composites. There is a commensurate decrease in the time it takes for the composites to set on account of the faster production of these additional products (Bouasker et al. 2008; Poppe and Schutter 2005; Ltifi et al. 2011).

3.1.3 Air Content

The incorporation of biochar into mortar mixtures resulted in an optimization of the amount of air in the mixtures (Gupta et al. 2018a, b, c, d). The rise in air content of the mortar mixtures with the addition of biochar was attributed to the porous character of biochar, in addition to the increased amount of free water available in the matrix and the presence of more free water in fresh cementitious mixtures leads to a larger air content (Mindess et al. 2003).

3.2 Mechanical Properties

3.2.1 Compressive Strength

Biochar prepared from wood wastes was shown to boost the compressive strength of mortar mixtures by up to 1% when Portland cement was replaced with biochar. When biochar was applied in higher concentration, its compressive strength was reduced. The higher absorption capacity of biochar from wood and mortar waste, which results in a lower binder ratio and a corresponding densified microstructure, was linked to the upgrading in strength. The greater strength can also be linked to the biochar particles pore filling ability, which also leads to a commensurate refinement of the microstructure (Choi et al. 2012; Restuccia et al. 2017; Cyr et al. 2005). Furthermore, the compressive strength of all biochar-containing mortar mixtures grew with age, demonstrating that adding biochar had no negative impact on the development of hydration reaction. The use of various types of biochar as a substitute for Portland cement in concrete resulted in a reduction in compressive strength. As the size of the biochar particles grows larger, the compressive strength decreases even more (Odimegwu et al. 2018).

3.2.2 Flexural Strength

The diluting influence on the cement, along with the accumulation of biochar particles, can be blamed for the decrease in flexural strength (Gupta et al. 2018a, b, c, d). The addition of higher biochar content has been shown to improve flexural strength. The pore-filling impact of the biochar, which provides a link between the components in the concrete and increases the flexibility of composite, was attributed to the improvement in flexural strength (Muthukrishnan et al. 2019). It has been observed that reducing the number of pores in concrete improves the flexural strength of construction material (Snoeck et al. 2014; Awoyera et al. 2019; Adesina and Awoyera 2019).

3.3 Durability Properties

3.3.1 Water Absorption

The use of biochar at a concentration of 2% resulted in a decrease in water absorption in connection with the depth of water penetration of the mortar mixtures (Gupta et al. 2018a, b, c, d). The decrease in absorption caused by the incorporation of biochar is attributable to a decrease in the porosity of the mixtures, which makes water infiltration more difficult (Akhtar and Sarmah 2018).

3.3.2 Shrinkage Properties

The shrinkage attributes of cementitious composites with biochar have received little attention. Nonetheless, it was shown that replacing cement with biochar resulted in early drying shrinkage (Gupta et al. 2018a, b, c, d). Later on, it was found that incorporating 1% biochar into mortar reduced drying shrinkage; however, the drying shrinkage of mortar containing 2% was greater than the control. Biochar can be employed as an internal curing agent to reduce shrinkage in cementitious composites due to its stable porous structure (Cosentino et al. 2019; Gupta et al. 2018a, b, c, d; Batista et al. 2018). In a study, it was observed that to prevent self-shrinkage in cement pastes, biochar can be used as an internal curing agent alongside magnesium oxide. The integration of biochar under the pretense of a 2% replacement for cement resulted in a 16% reduction in self-shrinkage. The progresses were credited with a considerable reduction (Mo et al. 2019).

3.3.3 Resistance to Elevated Temperature

Concrete mixtures including up to 2% wood waste biochar as a Portland cement replacement have been shown to ameliorate the durability of concrete at high temperatures (Gupta et al. 2020). At 550 °C of pyrolysis temperature, concrete compositions containing biochar lost nearly 4% of their mass, while concrete combinations containing simply Portland cement lost around 6% of respective mass. The higher pores in concrete integrating biochar, that prevented the accumulation of pressure within the composites, were attributed to the increased temperature resistance with the inclusion of biochar. In comparison to those prepared with solely Portland cement as a binder, biochar-infused concrete has been stated to have no serious cracking (Gupta et al. 2020).

4 Applications of Engineered Biochar for Geoengineering

Soil additives to promote water absorption, plaster to absorb humidity, and energy alternatives to supersede fossil fuels are all examples of current use of biochar (Joseph et al. 2007). Biochar has also been used in construction materials. In addition to abundance of properties of engineered biochar such as increased surface area, porosity, functional groups, and mineral content, biochar-based building materials provide the possibility of carbon-negative construction. The Ithaka Institute in Switzerland constructed the first building utilizing this material in 2013, and it is currently undergoing comprehensive performance testing. However, the structure already has proven to be extremely insulated and has excellent humidity control. There are also significant chances to employ the char-clay material to upgrade old buildings that have poor insulation, humidity issues, or contaminations like lead paint (Schmidt 2014).

4.1 Insulation Material

Due to the sheer ability of the pores of biochar to store water, biochar is an extremely efficient medium for storing moisture. The pores also trap significant amounts of nearly immobile air, making biochar one of the well-known insulating materials currently available. Low heat conductivity and potential to absorb water up to five times its weight are two of the characteristics of biochar. Due to these characteristics; biochar is an excellent substance for insulating buildings and for controlling humidity (Schmidh 2014).

4.2 Biochar-Based Clay and Lime Plasters

Biochar can be used as an additive for plaster at a ratio of up to 80% in combination with clay, lime and cement mortar. Biochar-based clay and lime plasters have been developed by Ithaka Institute, with black carbon accounting for up to 80% of the material. This high percentage is feasible because biochar may completely replace sand and the ensuing plaster is five times lighter in compared to the ordinary version because of its high porosity. Along with carbon storage, the biochar-clay plaster provides good insulation, humidity control, and electromagnetic radiation mitigation. This mixing produces inside walls with proper insulation and breathing capabilities, allowing for humidity levels in a space to be maintained at 45–70% in both summer and winter. This keeps the air within the rooms from becoming too dry, which can cause respiratory difficulties and allergies. It also keeps condensation from accumulating around thermal bridges and on the outer walls, thus preventing mold growth (Schmidth 2014). The interior climate of building is influenced by insulation, humidity, and electromagnetic radiation qualities. If a building is demolished, the biochar-based plaster can be recycled into the soil as a compost supplement, increasing the soil's carbon-trapping potential (Schmidt 2014).

4.3 Building Bricks, Tiles, and Concrete

Building materials including bricks and tiles can also be made from biochar. Earlier, biochar brick prototypes contained a binder substance such as cement or lime and had a tensile strength of 20 N/mm^2, whereas typical brick has a minimum tensile strength of about 3.5 N/mm^2. The research reveals that bricks built with 50% biochar and 50% high-density polyethylene had the maximum compressive strength and the biochar–cement brick outperformed in the context of insulating value, hardness, and water absorption (Barton et al. 2020). When using cement and lime, biochar can totally replace sand, lowering the weight of materials by a factor of five (Schmidth 2014). If used globally, the biochar–cement bricks would result in 6% reduction in CO_2 emissions from cement manufacture (Brownell 2021).

4.4 Biochar Roof Tiles

Biochar roof tiles were created in a similar way by a student team at Rochester Institute of Technology. Due to the expensive cost and the noise generated by the traditional roof tiles during rain, the students sought an alternative to the traditional sheet-metal roof. They designed a roof tile made from 30% biochar mixed with cement, sand, water, and reinforcing plastic from shredded waste soda bottles, resulting in a product that sequesters carbon and reduces overall embodied energy (Barton et al. 2020).

Results like these are relatively new, but intriguing. Rather than burying carbon with carbon capture and storage technology (CCS), we may utilize stored carbon in the construction of buildings to make a visible and functional contribution. Moreover, carbon-rich envelope materials can also be utilized to construct green walls and roofs, and they could play a new role once a building's useful life has passed.

5 Limitations of Engineered Biochar for Geoengineering

Biochar as a geoengineering material has only been studied in the lab. According to the existing research, biochar has yet to be deployed for a wide range of applications. Considering geoengineering applications, specifically for insulating materials, roof tiles, building bricks, tiles, and concrete, research is needed to establish these building materials on a large scale and its applicability in the field.

As discussed in this chapter, the engineered biochar can be accustomed into cementitious composites as a sustainable additive to enhance certain properties. Furthermore, the effect of biochar on the efficiency of composites varies greatly depending on the source, potential mechanism, and concentration of biochar used. As a result, certain considerations must be taken before biochar is applied to cementitious composites (Wani et al. 2021). There is an immediate need for a comprehensive study to be carried out to validate the research.

6 Conclusions and Future Prospects

Engineered biochar has made significant progress in recent years in terms of modification technologies along with environmental, agricultural, and energy storage purposes. Growing concern in the beneficial application of engineered biochar has spawned a slew of new scientific and engineering fields, particularly in the realms of environmental science and engineering. Along with its vast usage in the atmospheric, water, and soil systems, it plays an important role in promoting environmental sustainability. The methods of manufacture and modification, chemical and physical properties, and adsorption mechanisms have all been widely investigated up to this point. Biochar application as a construction material has a great potential. Carbon sequestration would be possible if biochar is used as construction materials. By doing so, the impact of construction material production on climate change will be reduced, as greenhouse emissions will be considerably decreased. As biochar bricks, plaster and concrete are generally inexpensive, environmental friendly, and easy to make, they are a safe alternative to cementitious materials and concrete. As a result, it is critical that such materials should be used to minimize the harmful levels of CO_2 in the atmosphere, to which the construction and building industry contribute significantly.

Given the focus on sustainable construction and recent advances in biochar research, more widespread utilization of biochar as a material used for construction, not only as a waste management method but also for carbon capture and storage technology (CCS), may be a realistic expectation. However, the identified technological and technical difficulties must first be addressed so that this could be achieved. To produce engineered biochar with physical properties suitable for CO_2 adsorption, effective raw material preparation and control of pyrolysis process parameters such as pyrolysis temperature, pressure as well as heating rate are critical. Tests on the endurance and structural qualities of biochar-concrete along with the associated economical, environmental, and social benefits of these new materials should also be studied. This will be particularly important to investigate how incorporating biochar into buildings and structures can result in broader sustainability benefits than just climate change mitigation. However, the effects of biochar dosage on the biochar long-term performance of cement require additional examination in future investigations.

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